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Abstract

Returning to the Moon . . . for industrialization! Habitats are the cost-effective way to house people on the Moon for more than a couple of days. NASA, universities, and aerospace companies have designed lunar habitats to house astronauts for their lunar tour of duty. Designs range from "campsites" to permanent "cities" for human development of the Moon, but the purpose is all the same: to provide shelter and a livable environment to enable the astronauts and mission equipment to fulfill the mission objectives.

The habitat design is influenced by the launch vehicle payload envelope, lunar environment, mission operations, degree of commonality/optimization, and necessary radiation protection. The mission requirements generally demand that the habitat provide support for extravehicular activity (EVA), thermal control, environmental control, life support, power, and communications and data handling (C&DH) to meet the industrialization objective. This paper discusses the above elements of the habitat design with respect to past study results performed by NASA, university, and aerospace companies.

Introduction

Lunar habitat elements consist of pressurized module(s), airlock(s), the support systems for the crew, and these containers, consumables, and experiment payloads. The mission requirements and priorities, such as cost, schedule, or mass, define the optimized configuration and system designs. Some requirements/constraints are constant (i.e., the lunar environment) and others are variables (i.e. mission requirements). A few of the many mission requirements which greatly affect the habitat design are crew size, duration, evolution plans, and required operations. This paper discusses the habitat elements and the effect of the requirements on these elements with an emphasis on the constant requirements.

Environment

A discussion of the full environmental characteristics of the Moon are beyond the scope of this paper. Only the characteristics which affect the habitat design are mentioned. A gravity one-sixth of the Earth's gravity is found on the Moon, but the launch forces must also be considered. The Moon has no atmosphere for human respiration, for thermal control, or for radiation protection, as is found in the Earth's atmosphere. A respirable atmosphere must be provided inside the habitat and EVA suits. The surface temperature ranges from −260 to 212 °F. The hottest thermal condition for the habitat and EVA crew members is at the lunar noon. The Earth's atmosphere protects people from much of the radiation from space. People on the Moon must be protected from radiation by the habitat and EVA suits. Electrostatically charged dust is found in large quantities on the surface of the Moon and on hardware and people on the Moon, especially to the heights of 1 m and below.

Figure 1 shows the lunar site locations from which direct communication with the Earth is possible.[1] All lunar sites bounded by the central contour in the figure can expect continuous communication with Earth. A site located in the blackened regions will see the Earth set below the lunar horizon, thus allowing direct communication only part of the time. Sites within the cross-hatched region are on the far side of the Moon and cannot communicate with Earth without the aid of a relay satellite or relay antennas on the lunar surface. The relatively small diameter of the Moon, 2,160 mi, impedes surface-to-surface direct communications. Satellites or an array of surface antennas are needed to accomplish communication on the surface outside the immediate area.

Figure 2 shows the length of the lunar daylight period for various site latitudes.[1] The days and nights at the equator are equally 14.7 Earth days long. The daylight period varies considerably for high latitudes due to the slight (1.5°) tilt of the lunar axis. The maximum elevation angle of the Sun observed from any lunar site is 90°-latitude+1.5°.

Volume

The interior layout must be very efficient if cost, volume, and mass constraints are present. The volume is directly dependent on crew size, layout efficiency, mission duration, and mission objectives. Figure 3 shows a starting point volume which is affected by mission objectives and inefficiencies.[2] Too small of a volume limits the crew's efficiency, placement of the equipment, and access to the equipment. Too large of a volume excessively increases the habitat, lander, and launch vehicle cost and mass through structure and system support. The objective of the volume analysis is to provide the volume required for an efficient mission while minimizing it at the same time.

Layout

The habitat layout should consider safety, cost, mass, interface constraints, and operational efficiency along with specific mission requirements. Safety must be considered for possible emergency situations. Two or more pressurized areas and exits are required to provide a safe haven in loss of pressure situations and guaranteed exit. The habitats' safety layout planning includes accessibility to necessities like water, EVA suits, entries, and the equipment to be repaired.

Electronics and crew require shielding from radiation. Uniform elements, those with a consistent density, are better radiation shields than electronics or other nonuniform elements. Water and tightly packaged food are examples of good shields. A solar shelter should be set up to protect the crew from a solar flare for up to 3 days by utilizing good shielding equipment around the protected area. Assess to water, food, and communications is required in the shelter. Utilizing existing elements wisely will minimize and possibly eliminate extra equipment sent for the exclusive purpose of radiation shielding.

The greatest drivers in the habitat's external design are the launch vehicle payload restrictions and interface with the lunar lander coupled with the load bearing requirements on a pressure shell and launch loads. Orbital assembly of the lunar elements is not desirable due to the complex operations and verification process. Many reasonable options for unloading the habitat from the lander exist, but increase the operational complexity of the mission.

The efficient layout of the interior of the habitat consists of a delicate balance of minimizing masses/volumes and operational efficiency. The module should be designed to provide the maximum usable volume and floor area for the associated structural mass. Equipment should be placed to promote productivity by congregating similar functional hardware, for example, food and galley equipment would be located together, EVA suits located near the airlock. Efficiency is also increased by optimizing the location of the most commonly utilized equipment and allowing easy access to required equipment and workstations.

Electrical cables, fire detection equipment, water lines and pumps, and gas lines can be minimized by congregating equipment with each of these characteristics. To illustrate this concept, consider congregating five electrical boxes in one location versus spreading these five boxes over a large area. The weight, volume, and risk of failure is smaller for the cooling loop, electrical cables, and fire detection of the congregated layout. One fire detection system satisfies safety requirements for the congregated layout, but many are required for the spread layout. Access to all the cooling loop, electrical cables, etc., is required for potential maintenance, but requires much volume to accomplish in the typical layout.

Dust problems can be minimized by a wise habitat design. The design can utilize the fact that dust generally falls to the floor in the lunar environment. Dust may infiltrate the area around the airlock through electrical charge crawling and on EVA support equipment and lunar samples. The "clean" functional areas, galley, electronics, and most science, should be well separated from the airlock area to minimize dust contamination. Various methods and types of dust collection may be employed in formulating a dust control system for a lunar habitat. Parts of the system may precede entry into the airlock in order to ease the cleaning load and disposal problem on the equipment located in the habitat.

Internal Pressure

Generally the optimum internal pressure to minimize the habitat's and internal experiments' cost is the Earth's atmospheric pressure, but the pressure differential between the EVA suits and the habitat should be minimized for safety reasons. Historical internal pressures used for NASA programs have ranged from 5 to 14.7 lb/in^2 to provide a livable environment for the astronauts.

The habitat module pressure is greatly influenced by the pressure used in the space suits for EVA. EVA productivity increases with the use of lower pressures because the suit, especially the glove, becomes more flexible. A lower suit pressure also lowers the mass of the space suits because a one, not two, gas life support system is sufficient. A one-gas life support system is needed for low pressures because people need only oxygen at the low pressures. The higher pressures require nitrogen and oxygen, thereby requiring a two-gas life support system.

The optimum pressure differential between the habitat and the EVA suits would be small for two reasons:

(1) Transfer between various pressures presents health risks directly proportional to the difference between the pressures. Much like scuba diving in water, the dangerous aspect of changing pressures is the formation and expansion of gas bubbles in the blood and lungs.

(2) Larger pressure differentials require the crew to breathe a median pressure, or prebreathe, for a defined period of time before EVA. Operational impacts due to prebreathe requirements increase as the pressure differential increases. Table 1 summarizes the other advantages of the low and high pressures.[3]

Table 1. Internal Pressure Characteristics

	Advantages of Low Pressures	Advantages of High Pressures
Safety/ Health	• Reduces the change in pressure between habitat and optimum EVA suit	• Low oxygen content reduces fire potential • Crew escape time increased • Less medical monitoring and countermeasures required
Cost		• Off-the-shelf equipment more easily utilized • Less testing required • Material selection greater • Limits variables for experiments
Systems	• Less resupply air required	• Easier to air cool electronics
Operations/Efficiency	• Less prebreathe time spent before EVA's (for optimum suit pressure)	• Sound transfer eases communication

Hopefully, a new EVA suit glove will be designed in the near future to minimize the operational inefficiency of the high pressure on the suits. This would solve the conflict between higher cost versus operational inefficiency.

Systems

One of the consistent issues for all system designs is the redundancy requirement. A quick trip to the hardware store is out of the question; on the other hand all spares increase the mass and volume. Commonality of smaller elements can increase redundancy for all those elements while minimizing mass. The usual categories of life critical and mission critical can be utilized along with reliability information about the equipment to fulfill safety and operational requirements during the mission without taking unnecessary spares.

Two trades for the habitat are commonality versus optimization and existing versus new technology. The newer technology hardware is usually lighter, riskier for the program schedule, more capable, and more expensive than older technology hardware. Consider the cost savings versus the higher mass and/or loss of efficiency of using "off the shelf" hardware.

Crew Systems

Crew systems provide crew support elements such as tools, chairs, beds, windows, storage, clothes, hygiene, food preparation, and many consumables for hygiene and food. Safety considerations suggest minimizing crew direct participation involving heavy equipment. Exercise equipment is required for longer durations as a countermeasure to lessen the effects of partial gravity. Health monitoring, emergency care, and off-hours recreation equipment are required for the crew, but the designs are related to the mission duration. Utilization of software and moveable, multiuse hardware could possibly provide mass savings for crew systems.

EVA Systems

The habitat or airlock must allow the crew to transfer into or out of the habitat. The habitat provides storage for the EVA suits, tools, maintenance equipment, and airlock function equipment. An airlock is mass justified as an addition to the habitat with around three to six planned EVA's, with the exact number being dependent on the module volume and airlock designs. Gases in the airlock must be vented or pumped out to allow access to the surface. Gasses in the airlock must be replaced to allow access to the habitat. Dust control should be provided before, during, and after crew transfer from the surface to the habitat to minimize the dust problem inside the habitat. Stowage and activity volume must be provided in the habitat and in the airlock for EVA preparation, egress, and ingress for at least two crew members at a time.

Servicing of the suits is required due to maintenance for normal wear and maintenance for the extra wear that the dust insures. One Apollo glove quit working due to dust. The habitat must provide for constant communications between the EVA crew and the habitat crew. Hyperbaric capability and/or incapacitated crew accommodation may be required for safety reasons. Hyperbaric capability is the ability to create a high pressure environment, 2.8 times atmospheric pressure, to treat crew members who might have medical problems due to pressure transition operations. The high pressures shrink gas bubbles in the body until the bubbles can dissolve. The incapacitated crew accommodation is the volume to fit a prone crew member and at least one medical attendant.

Communications and Data Handling (C&DH)

The habitat is typically required to communicate with the Earth, the lander, EVA crew members, and the rover. This list would vary for different missions. Communications with the rover or the other surface station may be limited by distance due to the relatively small diameter of the Moon. Data rates are primarily driven by the science and, therefore, will not be addressed in this paper except to point out that software should be considered in the cost estimate.

Environmental Control Life Support System (ECLSS)

This system is required to provide potable water, hygiene water, breathing gases in appropriate mixtures/pressures/air flows, fire detection/suppression, waste management facilities, dust/contaminant removal and water and atmosphere quality monitoring. The design is dependent on the crew size, mission duration, habitat volume, airlock volume and requirements, science requirements, decontamination requirements, internal pressure, and crew water requirements. Does the crew get a shower? Does the airlock have hyperbaric capability? How many fire detection systems are required for the layout? These questions along with the mission requirements previously mentioned affect the life support system hardware design too much to give even approximate cross over points for closed-system versus open-system trades.

Power System

Batteries, solar arrays, fuel cells, dynamic isotope system (DIPS), or a nuclear reactor are potential contenders for the habitat power source(s). Batteries are applicable only for very short durations. Solar arrays are currently in use, but lose efficiency in the hot temperature and dust environment of the Moon. Solar arrays without a secondary energy storage system are obviously only applicable for daytime use. Fuel cells are presently available, but regenerative fuel cells require some development. Solar arrays in conjunction with a regenerative fuel cell system is the most mature technology for day/night lunar power system of moderate power requirements. DIPS and nuclear reactors are not fully developed, but are reasonable candidates for the lunar environment—DIPS for small uses and nuclear for large. The nuclear reactor requires shielding and/or distance from the crew to prevent excessive radiation contamination.

Thermal Control System

A radiator or a radiator and heat pump combination are the primary contenders for habitat heat rejection. The wide range of temperatures may require fluid development and/or partial retraction of the radiator at night to prevent freezing of the working fluid. Ideally, the radiator would be parallel to the Moon surface. A 10° tilt in radiator results in approximately 5-percent loss in efficiency. A heat pump system would require further development for this environment. Dust problems are a concern for both systems, although the heat pump system is less sensitive to contamination than the simple radiator.

Radiation

The Earth's atmosphere protects us to some degree from radiation exposure, but the Moon lacks an atmosphere's protection. All electronics and materials used for the lunar habitat must be designed for the harsh radiation environment. People, however, are not designed for this radiation environment and must be shielded appropriately for the mission. The NASA human radiation exposure limits from NASA-STD-3000 are shown in Table 2.[4]

Table 2. Radiation Limits

Exposure Time	Blood Forming Organs	Eye	Skin
30 days	25 rem	100 rem	150 rem
Annual	50 rem	200 rem	300 rem
Career	100 to 400 rem	400 rem	600 rem

The crew receives radiation during space travel, EVA's, and in the habitat. They are exposed to radiation from solar flares during this time. The radiation comes from all directions except through the Moon itself. Additive analysis must be performed to determine the required habitat shielding required to prevent the above limits to be exceeded. Habitat radiation doses are analyzed using the three greatest solar flares of February 1956, August 1972, and October 1989.

Most lunar missions consider only solar flare radiation, but if the crew is to stay for long periods of time, then galactic cosmic radiation must also be used in this analysis. "Long periods of time" has not been defined, but is somewhere in the neighborhood of 6 months to a year. The Sun cycles roughly every 11 years from periods of low continuous radiation and more solar flares to higher continuous radiation and fewer solar flares. Solar flare radiation doses are easily higher than the above limits and are not predictable with much accuracy over more than 3 days, thereby requiring radiation protection for the astronauts inside the habitat. Solar flare shielding is partially, or if carefully designed, wholly provided by the pressure shell and any equipment around the astronauts.

Conclusion

The habitat must be designed to meet the mission requirements within the Moon's gravity, atmosphere, radiation, dust, and temperature characteristics. The interior layout must be very efficient if cost and mass constraints are present. The habitat layout should consider safety, cost, mass, handling constraints, interface constraints, and operational efficiency along with specific mission requirements. The optimum internal pressure to minimize the habitat's and internal experiments' cost is the Earth's atmospheric pressure, but the pressure differential between the EVA suits and the habitat should be minimized for safety reasons. The systems required to support the habitat and the crew are crew systems, EVA systems, communications, data handling systems, environmental closed life support system, power system, and the thermal system.

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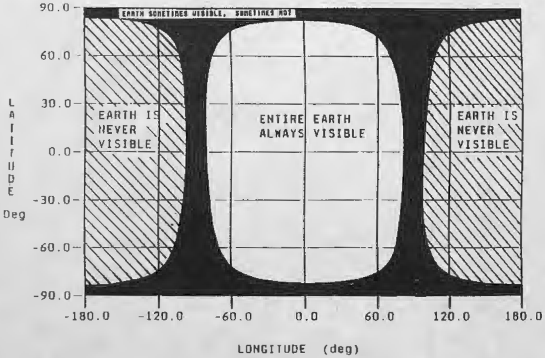

Figure 1. Lunar Site Locations Providing Continuous Earth Visibility.

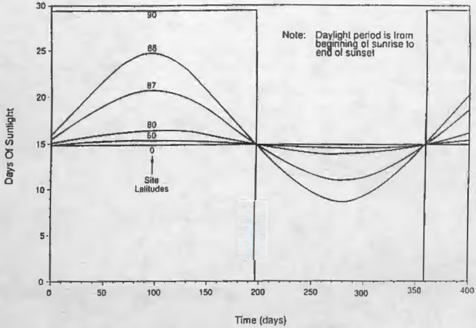

Figure 2. Length of Daylight Period for Northern Lunar Latitudes.

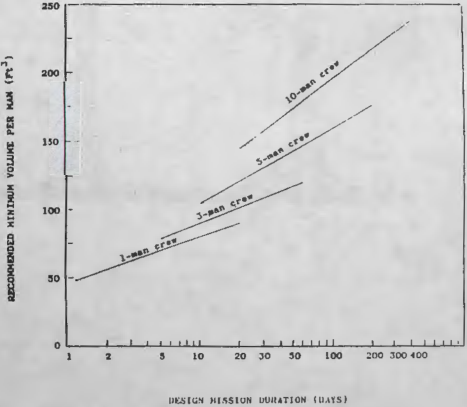

Figure 3. Habitat Volume Estimate Per Person.